



Measurement of $W\gamma$ and $Z\gamma$ Production in pp Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

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On behalf of the ATLAS Collaboration

Duke University



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e and γ ID
 γ Isolation

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The $W\gamma$ and $Z\gamma$ productions are direct test of the non-Abelian nature of the Electroweak theory

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The $W\gamma$ and $Z\gamma$ productions are direct test of the non-Abelian nature of the Electroweak theory

- Probing the $WW\gamma$ triple gauge boson coupling (TGC)

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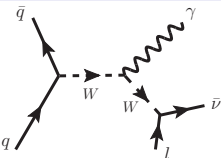
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$WW\gamma$ TGC





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- Probing the presence of $ZZ\gamma$ and $Z\gamma\gamma$ TGC forbidden (at the tree level) in the Standard Model

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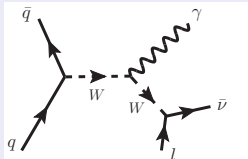
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- Highest cross sections among all diboson processes

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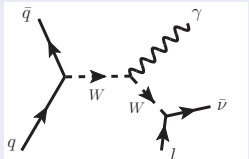
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- Highest cross sections among all diboson processes
- Amplitude interferences between u – and t –channel suppresses the $W\gamma$ production w.r.t. $Z\gamma$ production

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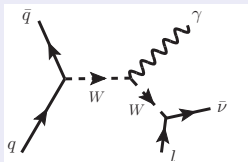
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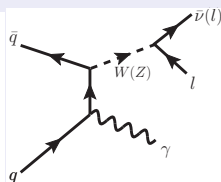
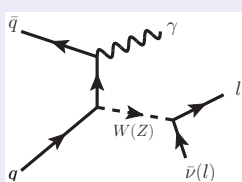
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ISR Production (u – and t –channel)





Signal Definition: $l\nu\gamma$ and $ll\gamma$ final states

The experimental signature of these processes are the
 $l\nu\gamma+X$ and $ll\gamma+X$ final states.

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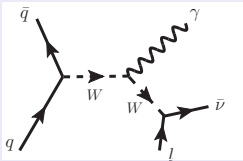
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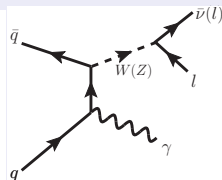
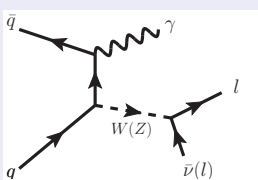
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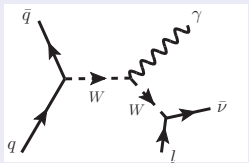
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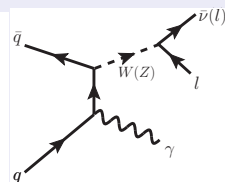
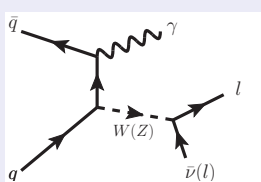
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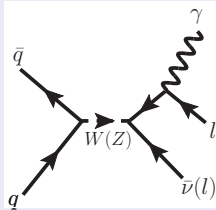
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- QED FSR from $W(Z)$ inclusive production
 - Dominating for $E_T^\gamma \lesssim 40$ GeV

QED FSR





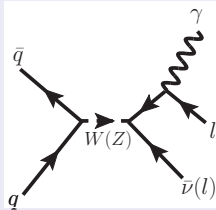
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QED FSR





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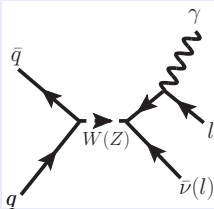
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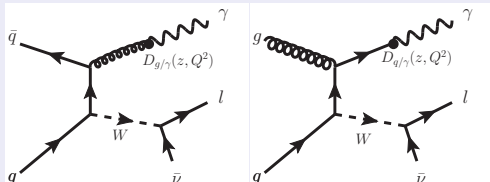
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 - Dominating for $E_T^\gamma \lesssim 40$ GeV
- High order $\mathcal{O}(\alpha\alpha_S)$ contributions (NLO corrections)
- Photons from fragmentation of jets produced in association with a W or a Z boson ($W(Z)+\text{jet}$ events)

QED FSR



"Fragmentation" Photon Production





Fragmentation Photon Contribution

Photons from fragmentation of jets produced in association with a W or a Z boson ($W(Z)$ +jet events)

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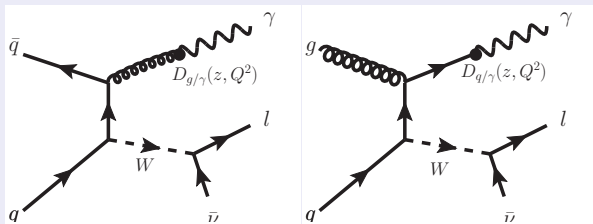
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"Fragmentation" Photon Production





Fragmentation Photon Contribution

Photons from fragmentation of jets produced in association with a W or a Z boson ($W(Z)$ +jet events)

- Only the sum of the prompt and fragmentation components is physically well defined \Rightarrow **Part of the signal**

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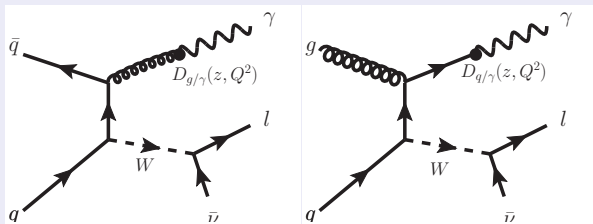
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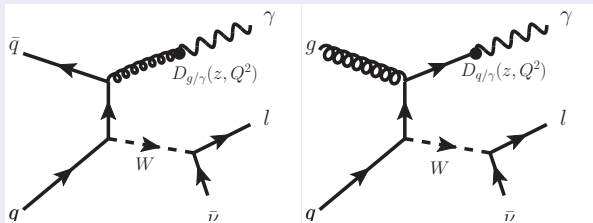
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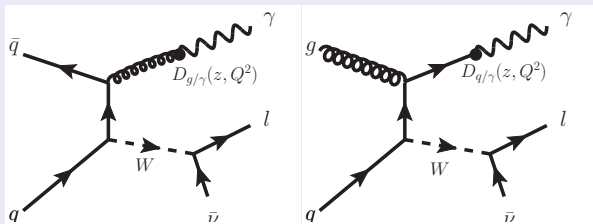
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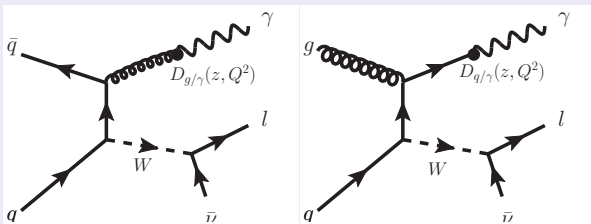


Fragmentation Photon Contribution

Photons from fragmentation of jets produced in association with a W or a Z boson ($W(Z)$ +jet events)

- Only the sum of the prompt and fragmentation components is physically well defined \Rightarrow **Part of the signal**
- Strongly suppressed by the photon identification and isolation requirements, but still significantly contributing
- Because of collinear divergences the measurements are restricted to events with $\Sigma E_T^{had} < 0.5 \cdot E_T^\gamma$
- Experimentally challenging because of large uncertainties in estimating its contribution in data, and because of a very different identification efficiency w.r.t. “prompt” photons

“Fragmentation” Photon Production





A Toroidal LHC Apparatus

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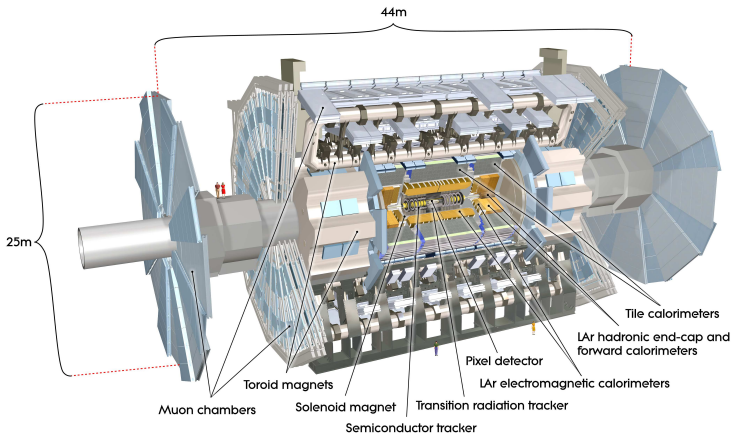
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Pixel Tracker

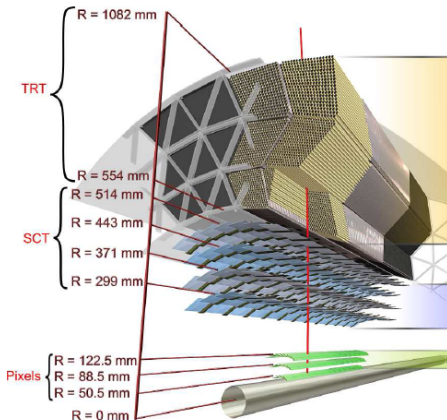
3 Barrel, 2×3 Endcap Layers
Resolution: $10 \mu\text{m}$ ($R\phi$)
60M Channels

SCT Tracker

4 Barrel, 2×8 Endcap Layers
Double Stereo Sides
Resolution: $17 \mu\text{m}$ ($R\phi$)
6.3M Channels

TRT Tracker

73, 2×160 Layers
About 30 hits/track
Resolution: $130 \mu\text{m}$ ($R\phi$)
PID Capability
 $\sim 0.3\text{M}$ Channels



Silicon Pixel, Silicon Strips, Transition
Radiation Detectors

Coverage: $|\eta| < 2.5$ in 2T B-field

$$\sigma/p_T^2(\text{GeV}) \sim 3.8 \cdot 10^{-4} \oplus 0.015$$



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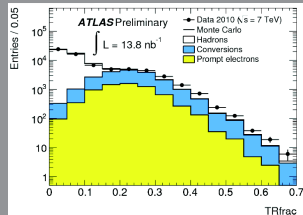
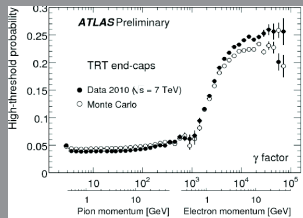
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PID Capability
 $\sim 0.3M$ Channels

e/π Separation in TRT

Transition radiation depending on the charge particle Lorentz factor γ

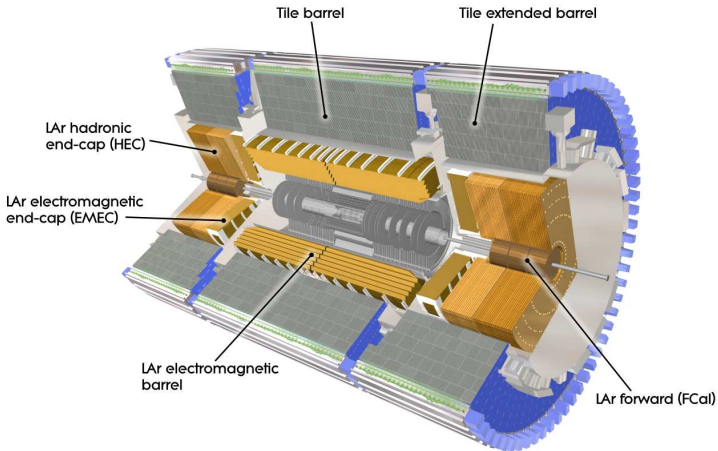




The Electromagnetic Calorimeter

Liquid Argon and Lead with accordion geometry
Coverage: $|\eta| < 3.2$ (with forward ECAL $|\eta| < 4.9$)

Three longitudinal samplings (plus a thin pre-sampler for $|\eta| < 1.8$)
 $\Delta E/E \sim 10\%/\sqrt{E(\text{GeV})}$



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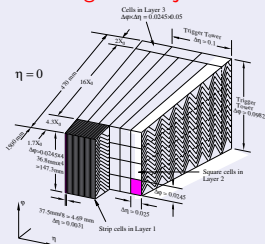
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EM Granularity

Longitudinal segmentation for maximum
background rejection



Second layer collect most of the EM shower energy

(cell $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$)

First (strip) layer with high granularity

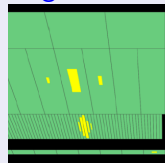
(event-by-event π^0/γ discrimination)

Third layer for tails of very high EM shower

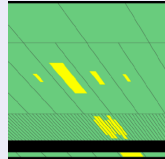
Pre-sampler for energy loss corrections

π^0/γ Discrimination

Single Photon



π^0 Candidate





Electron and Photon Identification

EM object identification algorithm

fully exploits the longitudinal segmentation of the EM calorimeter, the tracking information and the TRT particle identification capability.

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Identification Discriminants

- Hadronic energy leakage
- Middle layer energy and lateral width (R_ϕ , R_η)
- Strip layer lateral shower
- Strip layer first and second maximum energy ratio
- Track quality
- Track/Calorimeter matching
- First pixel layer hit
- E/p ratio
- Transition radiation probability

Three (Two) baseline set of identification cuts
for electrons (photons)

Optimized in E_T and η binning for uniform efficiency. For photons optimized separately for converted and unconverted photons



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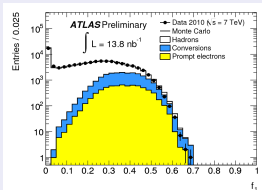
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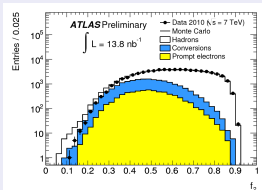
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e^- : EM Fraction in Layer 1



e^- : EM Fraction in Layer 2





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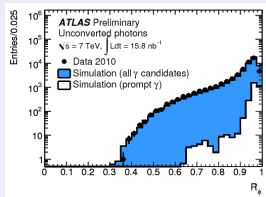
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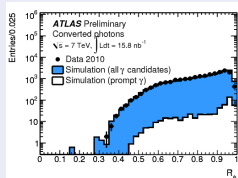
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γ unconverted: R_ϕ



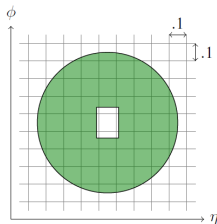
γ converted: R_ϕ





Photon Energy Isolation

- Transverse energy in a cone with $R = 0.4$ around the photon
- Taken as a sum of uncalibrated cell energy
- Central core 5×7 not included
- Corrections for *out-of-core* leakage
- In principle sensitive to underlying event and pileup....



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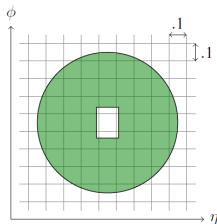
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- In principle sensitive to underlying event and pileup....
- “Ambient” energy density measured by looking at underlying event in additional cones in the same event (method proposed by Cacciari, Salam, Sapeta, and Soyez)

<http://arxiv.org/abs/0912.4926>





Photon Energy Isolation

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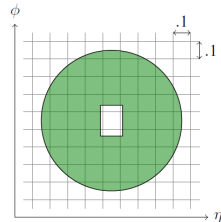
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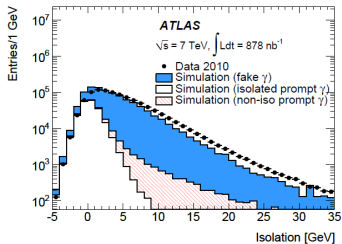
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- “Ambient” energy density measured by looking at underlying event in additional cones in the same event (method proposed by Cacciari, Salam, Sapeta, and Soyez)

<http://arxiv.org/abs/0912.4926>

- Photon energy isolation different for direct photons and photon from fragmentation





Event Selection

Require an high E_T photon on W(Z) candidate events

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W Selection

- One lepton with $E_T > 20$ GeV
- $|\eta| < 2.47$ (e) or $|\eta| < 2.4$ (μ)
- $E_T^{miss} > 25$ GeV
- $m_T^W > 40$ GeV
- Veto on a second lepton



Event Selection

Require an high E_T photon on W(Z) candidate events

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Z Selection

- Two leptons with $E_T > 20$ GeV
- $|\eta| < 2.47$ (e) or $|\eta| < 2.4$ (μ)
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Event Selection

Require an high E_T photon on W(Z) candidate events

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Photon Selection

- One photon with $E_T > 15$ **GeV** and $|\eta| < 2.37$
- $\Delta R(l, \gamma) > 0.7$
- **Isolation Energy** $E_T^{iso} < 5$ **GeV**



Event Selection

Require an high E_T photon on W(Z) candidate events

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- One photon with $E_T > 15$ GeV and $|\eta| < 2.37$
- $\Delta R(l, \gamma) > 0.7$
- Isolation Energy $E_T^{iso} < 5$ GeV

Number of Candidates
in 35 pb^{-1}

$W\gamma$: 192

$95 (e\nu\gamma) + 97 (\mu\nu\gamma)$

$Z\gamma$: 48

$25 (e^+e^-\gamma) + 23 (\mu^+\mu^-\gamma)$



Candidate Event Kinematic Distributions

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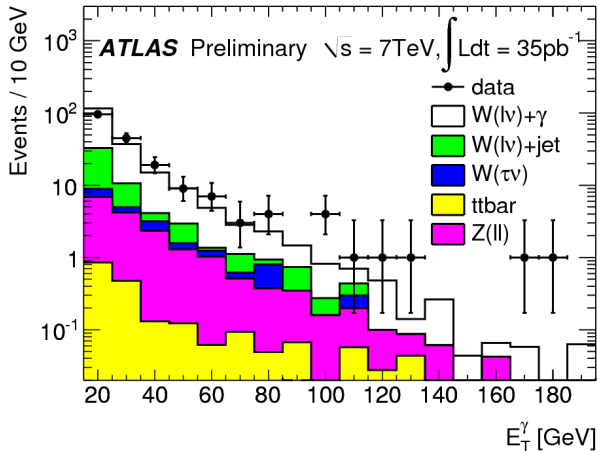
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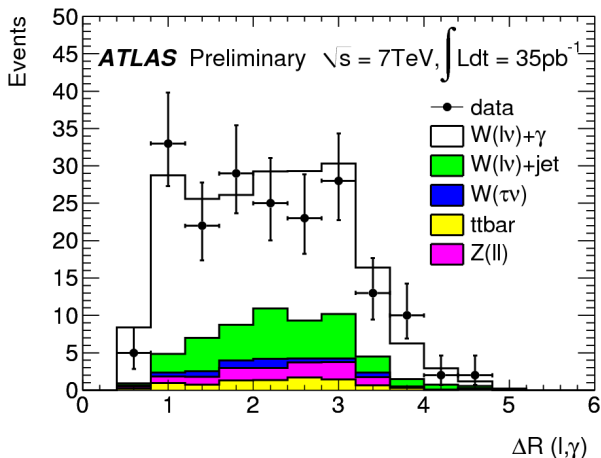
$W\gamma$ Candidates: Photon E_T Distribution





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$W\gamma$ Candidates: $\Delta R(l, \gamma)$ Distribution





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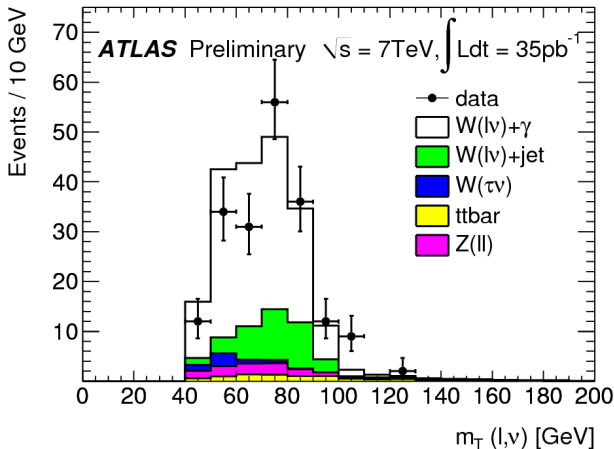
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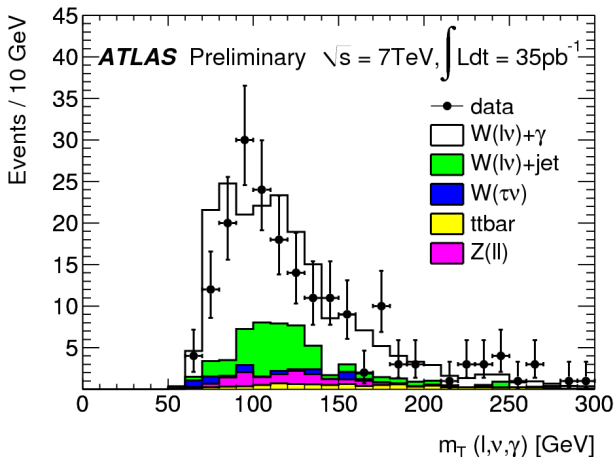
$W\gamma$ Candidates: $m_T(l, \gamma)$ Distribution





Candidate Event Kinematic Distributions

$W\gamma$ Candidates: $m_T(l, E_T^{miss}, \gamma)$ Distribution



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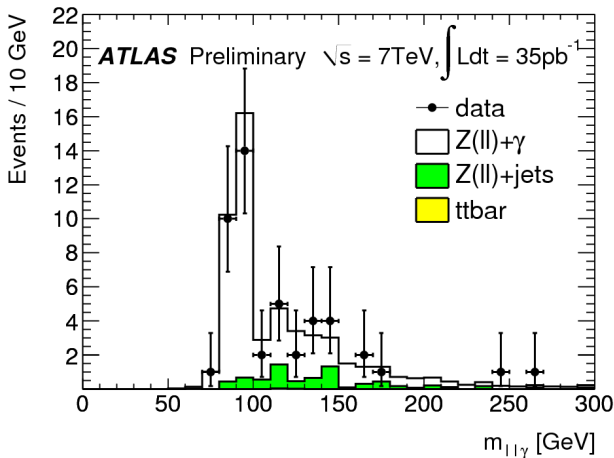
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Candidate Event Kinematic Distributions

$Z\gamma$ Candidates: $m_{l,l,\gamma}$ Distribution





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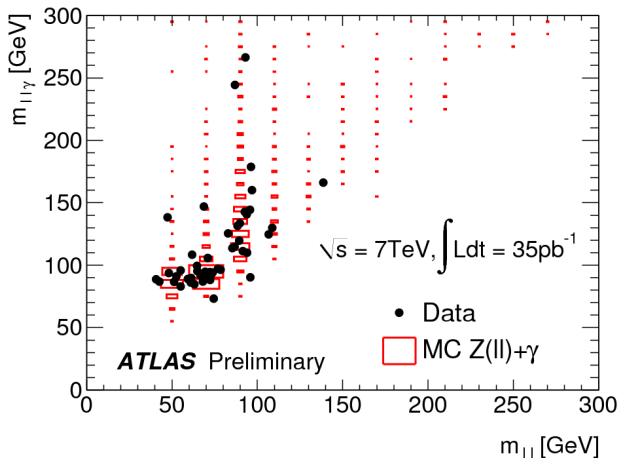
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$Z\gamma$ Candidates: $m_{l,l,\gamma}$ vs. $m_{l,\gamma}$





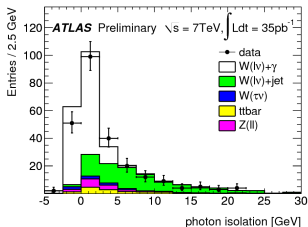
Signal Yield Extraction

A 2D-sideband method is used to extract the signal yield directly from $W\gamma$ and $Z\gamma$ candidate events

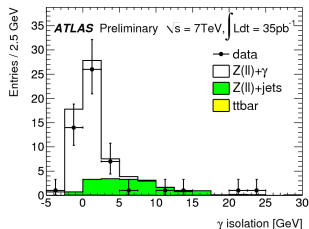
Discriminating Variable: Isolation Energy

Isolation Energy Distributions

$W\gamma$ Events



$Z\gamma$ Events



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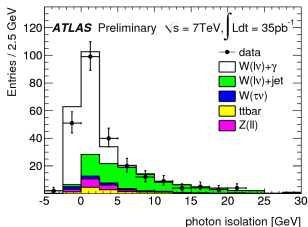
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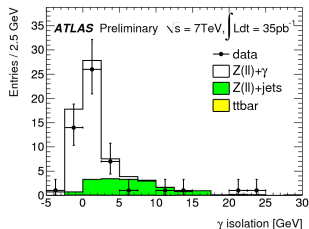
Discriminating Variable: Isolation Energy

Isolation Energy Distributions

$W\gamma$ Events



$Z\gamma$ Events



Isolation background shape from data.

Normalization from the tail of the isolation distribution.



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To model the background isolation energy distribution:

reverse some photon ID cuts

- Photons are required to pass the ID cuts except the strip layers variables
- Assuming no/little correlation between photon ID variables and isolation
 - Strip variables fairly uncorrelated with isolation energy



Signal Yield Extraction

To model the background isolation energy distribution:

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- Photons are required to pass the ID cuts except the strip layers variables
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 - Strip variables fairly uncorrelated with isolation energy

Method applied only to the $W\gamma$ analysis
(very limited statistics on $Z\gamma$)

- Corrections for signal presence in control region applied
- Contributions from other processes ($W \rightarrow \tau\nu$, $t\bar{t}$, $Z \rightarrow ee$, etc..) estimated from MC.
- Systematics due to the assumptions of the method and the definition of the control regions carefully estimated.

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To model the background isolation energy distribution:

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 - Strip variables fairly uncorrelated with isolation energy

Results: signal purity in selected events $\sim 80\%$

Process	Observed events	non W+jets background	W+jet background	Extracted Signal
$pp \rightarrow e\nu\gamma$	95	$10.1 \pm 0.8 \pm 1.2$	$16.9 \pm 6.4 \pm 7.3$	$67.9 \pm 9.5 \pm 7.3$
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Cross Section Calculation

$$\sigma_{pp \rightarrow l\nu\gamma(l+l-\gamma)} = \frac{N_{W\gamma(Z\gamma)}^{sig}}{C_{W\gamma(Z\gamma)} \cdot L_{W\gamma(Z\gamma)} \cdot A_{W\gamma(Z\gamma)}}$$

- N^{sig} is the number of the extracted signal events
- L is the the integrated luminosity
- C summarizes the reconstruction and identification efficiency
- A is the acceptance of the “total” cross section

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- N^{sig} is the number of the extracted signal events
- L is the the integrated luminosity
- C summarizes the reconstruction and identification efficiency
- A is the acceptance of the “total” cross section

Cross section measured in two phase-space regions:

Fiducial Phase-space where the measurement has been performed (defined by the cuts reported earlier in the “selection slide”)

Total Phase-space extended to regions outside experimental acceptance:

fiducial \rightsquigarrow **total** extrapolation done with Monte Carlo
“Total” phase-space definition:

$$E_T^\gamma > 10 \text{ GeV}, \quad \Delta R(l, \gamma) > 0.5, \quad \Sigma E_T^{had} < 0.5 \cdot E_T^\gamma$$

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Efficiency Values and Uncertainties

$$C_{W\gamma} (e \text{ channel}) = 36\% \quad C_{W\gamma} (\mu \text{ channel}) = 46\%$$

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Efficiency Values and Uncertainties

$$\begin{aligned}C_{W\gamma} (e \text{ channel}) &= 36\% & C_{W\gamma} (\mu \text{ channel}) &= 46\% \\C_{Z\gamma} (e \text{ channel}) &= 29\% & C_{Z\gamma} (\mu \text{ channel}) &= 43\%\end{aligned}$$

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Efficiency Values and Uncertainties

$$C_{W\gamma} (e \text{ channel}) = 36\% \quad C_{W\gamma} (\mu \text{ channel}) = 46\%$$
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Efficiency Uncertainties

Composition	$\delta C_{W\gamma}/C_{W\gamma}$	$\delta C_{Z\gamma}/C_{Z\gamma}$	$\delta C_{W\gamma}/C_{W\gamma}$	$\delta C_{Z\gamma}/C_{Z\gamma}$
	$e\nu\gamma$	$e^+e^-\gamma$	$\mu\nu\gamma$	$\mu^+\mu^-\gamma$
Trigger efficiency	1%	0.02%	0.6%	0.2%
lepton reconstruction and identification efficiency	4.5%	5%	0.5%	1%
muon isolation efficiency	-	-	1%	2%
photon reconstruction and identification efficiency	11.5%	11.5%	11.5%	11.5%
EM Energy scale and resolution	3%	4.5%	4%	3%
Momentum scale and resolution	-	-	0.3%	0.5%
E_T^{miss} scale and resolution	2%	-	2%	-
Problematic regions in the calorimeter	1.4%	2.1%	0.7%	0.7%
FSR modelling	0.3%	0.3%	0.3%	0.3%
photon isolation cut efficiency	6%	6%	6%	6%
Total uncertainty	14.3%	14.6%	13.8%	13.5%

Main contributions to the total uncertainty are:

- Fragmentation photon contribution in data (6% for both photon ID and isolation efficiency)
- Amount of material knowledge (particularlry at high $|\eta|$)
- Data/MC discrepancies for the EM shower shape distributions



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Fiducial Cross Sections

	$\sigma^{fid}[pb](\text{measured})$	$\sigma^{fid}[pb](\text{predicted})$
$pp \rightarrow e\nu\gamma$	$5.1 \pm 0.7(stat) \pm 0.9(syst) \pm 0.6(lumi)$	$4.6 \pm 0.3(syst)$
$pp \rightarrow \mu\nu\gamma$	$4.2 \pm 0.6(stat) \pm 0.7(syst) \pm 0.5(lumi)$	$4.9 \pm 0.3(syst)$
$pp \rightarrow e^+e^-\gamma$	$2.0 \pm 0.6(stat) \pm 0.5(syst) \pm 0.2(lumi)$	$1.7 \pm 0.1(syst)$
$pp \rightarrow \mu^+\mu^-\gamma$	$1.3 \pm 0.3(stat) \pm 0.3(syst) \pm 0.1(lumi)$	$1.7 \pm 0.1(syst)$



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$pp \rightarrow \mu^+\mu^-\gamma$	$1.3 \pm 0.3(stat) \pm 0.3(syst) \pm 0.1(lumi)$	$1.7 \pm 0.1(syst)$

Total Cross Sections

	$\sigma^{total}[pb](\text{measured})$	$\sigma^{total}[pb](\text{predicted})$
$pp \rightarrow e\nu\gamma$	$73.9 \pm 10.5(stat) \pm 14.6(syst) \pm 8.1(lumi)$	$69.0 \pm 4.6(syst)$
$pp \rightarrow \mu\nu\gamma$	$58.6 \pm 8.2(stat) \pm 11.3(syst) \pm 6.4(lumi)$	$69.0 \pm 4.6(syst)$
$pp \rightarrow e^+e^-\gamma$	$16.4 \pm 4.5(stat) \pm 4.3(syst) \pm 1.8(lumi)$	$13.8 \pm 0.9(syst)$
$pp \rightarrow \mu^+\mu^-\gamma$	$10.6 \pm 2.6(stat) \pm 2.5(syst) \pm 1.2(lumi)$	$13.8 \pm 0.9(syst)$

All cross section measurements are consistent within their uncertainties with the Standard Model expectations



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First measurement of $W\gamma$ and $Z\gamma$ production cross sections at $\sqrt{s} = 7$ TeV performed by ATLAS using $\sim 35 \text{ pb}^{-1}$ of integrated luminosity

Experimental measurements are in agreement with Standard Model expectations within error

With more data available this year the Triple Gauge Couplings will be probed with unprecedented precision

Searches will be extended also to $W\gamma$ and $Z\gamma$ resonance decay of particles beyond Standard Model

Stay Tuned for New Results Very Soon!



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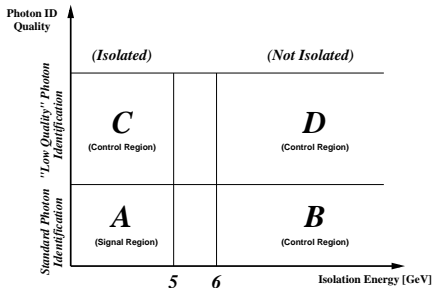
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- Assuming no/little correlation between photon ID variables and isolation:

$$\frac{N_D}{N_B} = \frac{N_C}{N_A}$$

for background events

- With small signal contamination in the control regions,
 N_B , N_C , and N_D from data
 \Rightarrow amount of background in N_A





Signal Yield Extraction

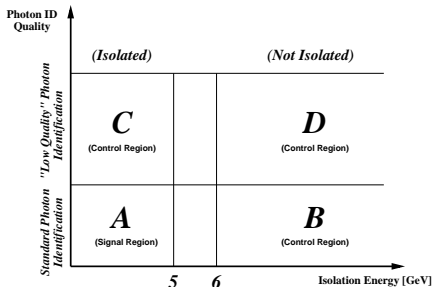
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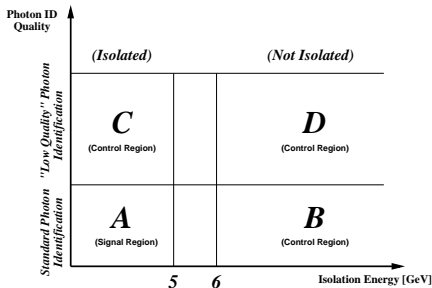
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Process	Observed events	non W +jets background	W +jet background	Extracted Signal
$pp \rightarrow e\nu\gamma$	95	$10.1 \pm 0.8 \pm 1.2$	$16.9 \pm 6.4 \pm 7.3$	$67.9 \pm 9.5 \pm 7.3$
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Signal purity in selected events $\sim 80\%$

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